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PROMOTION OF YOUNG SCIENTISTS IN LCA

Integration of spatial analyses into LCA—calculating GHG emissions with geoinformation systems

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Abstract

Purpose Spatial analyses in life cycle assessments are hardly ever conducted. The combination of geoinformation systems and life cycle assessments (LCA) databases is a way to realise such complex calculations. By the example of energetic utilisation of biomass via conditioned biogas a geoinformation systems-based calculation tool is presented which combines geodata on biomass potentials, infrastructure, land use, cost and technology databases with analysis tools for the planning of biogas plants to identify the most efficient plant locations, to calculate balances of emissions, biomass streams and costs.

Methods The calculations include the impact categories greenhouse gases, acidification, and eutrophication and were tested for the Lower Rhine region and the Altmark region in Germany. The results of the greenhouse gas (GHG) balances are presented. By using only nationwide available datasets, the calculation tool can be used in other regions as well.

Results and discussion Balances of individual sites, regional balances and their temporal development can be calculated in geoinformation systems (GIS) using LCA methods. The composition of the substrates varies according to site and catchment area and lead to large variations in plant configurations and the resulting GHG balances and cost structures.

Conclusions GIS tools do not only allow the assessment of individual plants, but also the determination of the GHG reduction potential, the biogas potential as well as the necessary investment costs for entire regions. Thus, the exploitation of regional biogas potentials in a way that is sustainable and climate-friendly becomes simple.

Keywords Biogas · Biomass · Calculation tool · Geoinformation system · GHG emissions · Spatial analysis

1 Introduction

There are a number of studies (Murphy et al. 2004) which prove in general the contribution to climate protection of biogas utilisation but an evaluation of regional distinctions and structural differences in particular is still missing. The assumption that the use of biomass automatically leads to saving of greenhouse gas emissions has to be proved with regard to the respective case when the balance shall reflect spatial circumstances on a small scale. Greenhouse gases are emitted while producing fertilisers and pesticides, during farming processes, in transportation purposes as well as in the operation of biogas plants. Moreover, the greenhouse gas saving depends on the efficiency of the entire chain of use and on the reference fossil technology that is replaced in each case (Börjesson and Berglund 2007; SRU 2007).

Life cycle assessments (LCA) are normally product-based balances used to compare a constant output which is the subject of assessment against a constant input. The inputs which are raw materials and preliminary products of constant quality are the investigated subjects of the inventory. In particular with agricultural preliminary products, there are

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variations in the inventory which are due to regionally different production capacities per area unit and changes in micro-spatial environmental parameters, although the end product always has the same quality and requirements of input material. The present approach comprises a spatial analysis of the inventory with geoinformation systems (GIS) in order to prepare spatially differentiated life cycle assessments.

In literature, there can be found only few similar approaches going into this direction which may be classified roughly into two theoretical groups of methodology: one part of the studies is based on the clustering of areas for the visualisation of spatial differences for areas with inherent differences of site-related aspects. Starting from this, a certain amount of inventory data sets is produced which serve to set up the life cycle assessment of each area (Yi et al. 2007; Ziegler et al. 2003). This can also be achieved by including general site parameters in the assessment process (Potting and Hauschild 1997, 2006) which can be combined with temporal characterisation factors (Shah and Ries 2009). Another approach is the introduction of additional impact categories, as it has been done for the integration of biodiversity, desertification and water balance aspects into the LCA (Geyer et al. 2010a, b; Núñez et al. 2010; Heuvelmans et al. 2005).

The approach presented here is targeted to integrate inventory data sets directly into a GIS application in order to analyse the production and related emissions and costs of upgraded biogas (biomethane). Once produced, biomethane can be injected into the gas grid and used for heat production, generation of electric power or combined heat and power and as fuel for vehicles (Tricase and Lombardi 2009; Urban et al. 2008). Applying a customised GIS application the determination of biomethane potentials coupled with GHG balances is possible.

2 Data and methods

2.1 Geoinformation systems and life cycle databases

There are various programmes and tools for carrying out IT-supported LCA which enable and facilitate the administration, analysis and most important the visualisation of material flows, processes or products and the calculation of eco-balances. The underlying databases contain material balances (inventories) which comprise input and output flows of processes. This inventory can be understood as a list of the resources consumed and the emissions associated with the system. In the present, our approach is to set the resource consumption into a spatial context with the connection of agricultural databases for the need of supplies and axillaries, emission factors from LCA databases (Ecoinvent 2004; IPCC 2007) and spatial information from geodata within a geoinformation system.

Information systems support technical and organisational facilities with comprehending, saving, converting and displaying information but pursue different goals (Bill 1999). GIS are designed to work with spatial data (geodata). The general concept of GIS is to query and analyse spatial data. Spatial data usually consist of a geometry representing the shape on the earth surface and attributive data, which provide alphanumeric information about the geometry. Generally, but especially while handling huge amounts of data, GIS are used in combination with external databases. Anytime the term GIS is mentioned in this article, it refers to this combination.

GIS are employed to construct a spatial model of the technological pathway biomethane production as described as a process chain in Fig. 1. The process chain is the visualisation of the system boundaries. In this context, it consists of different chain links—starting on the agricultural field or the livestock farm, over the transport route to the location of the biogas plant and ending before the entry point to the gas grid directly after the upgrading to biomethane. The complete chain is modelled by different kinds of geodata. Geodata from the Integrated Administration and Control System representing agricultural fields are integrated as well as geodata from the veterinary offices representing the livestock farms. TeleAtlas routing data are employed for modelling transport routes. For the spatial representation of (theoretical) biogas plant locations a methodology for site finding is integrated into the GIS application. This module makes use of data representing the current land use (digital landscape models) provided by the Federal Agency for Cartography and Geodesy. Additional data on nature protection zones was provided by the respective regional administration. Data regarding the gas grid is elaborated by applying webservice technologies, described in more detail within the next section.

The GIS is built up on the basis of ESRI products. ArcGIS on the ArcInfo level is deployed also using the extensions SpatialAnalyst and NetworkAnalyst. Many tasks are automated by encapsulated modules. These modules are implemented using ArcObjects and Microsofts VB.net technologies. Other modules are written in Python, an open-source scripting language. The python modules are integrated into the ArcToolbox. All modules can be run independently or can be run in sequence. For the integration of gas grid databases through a SOAP-web-service different gas grid operators are able to connect their GI and database systems to desktop applications as a reference system. The web-based request offers some advantages compared to the implementation of detailed gas grid information in a central system. This method ensures that the data acquired from the gas grid operator for analysis of local conditions is always up-to-date. A sophisticated data administration and update becomes needless.

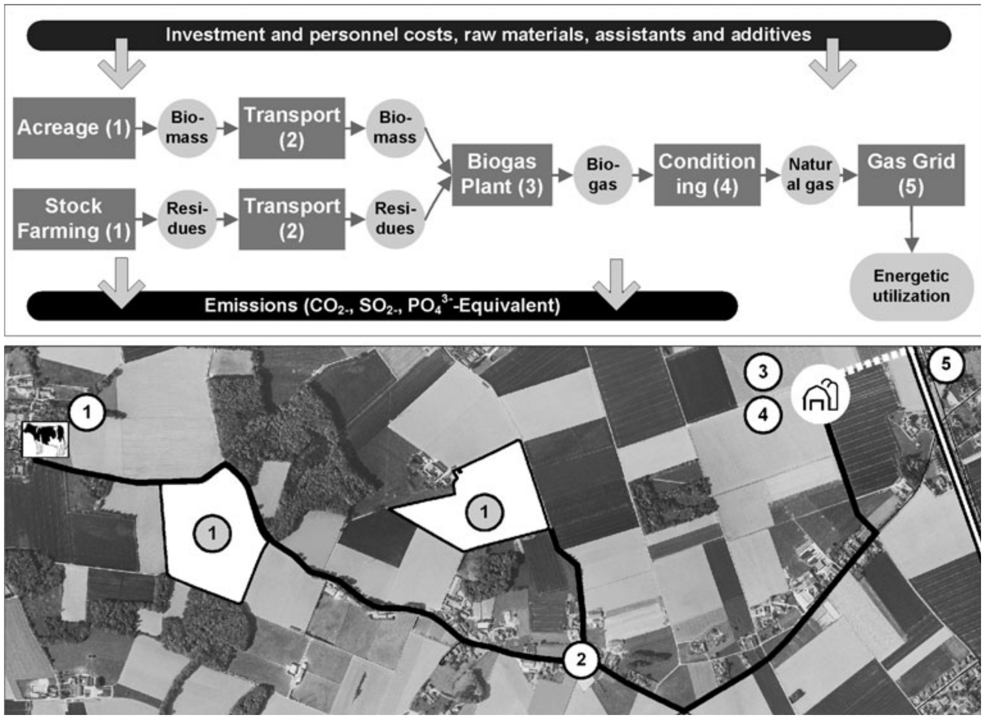


Fig. 1 Process chain of biogas injection

2.2 Structure of the model

The GIS model of the process chain is the basis for the GHG balance of the biomethane production. The calculation of GHG emissions is wrapped into a GIS-based catchment area analysis for biogas plants. The overall methodology is described in Fig. 2. The general principle is to calculate site- and plant-specific balances of material flows, costs and emissions released along the aforementioned process chain. The upscaling of a site-specific balance within one catchment area leads to a regional balance.

The catchment area analysis is composed of different steps. These are:

1. Site identification
2. Definition of catchment area
3. Selection of agricultural areas inside the catchment area
4. Inventory analysis
5. Impact assessment

In the module “site identification”, suitable sites for biogas plants for the injection into the gas grid are identified. Based on the current land use and legal restrictions of regional planning, a first estimation for a location of a biogas plant is deduced. Environmental aspects and approval procedures for building biogas plants are analysed in this module. This module differentiates areas where building is not possible from those where setting up a biogas plant is permitted. Areas without such restrictions are considered to be preferred sites for the building of a biogas plant. With the help of the gas grid webservice, the suitability for injection is verified.

Around a potential biogas plant site, catchment areas are calculated with the help of the ESRI Network Analyst and on the basis of the routing street network data (Fig. 3). These areas are based on maximum transport distances for the biogas substrates. The catchment area guarantees that all fields and livestock farms are within a certain transport distance from the biogas plant. Different agricultural fields are selected by chance within the module parcel selection. The amount of fields is determined by the regional availability of fields integrated by the application of RAUMIS (Gömann et al. 2008; Breuer and Holm-Müller 2006). The randomly selected fields together with the livestock farms setup the amount of substrate leading to the amount of biomethane to be produced by the biogas plant. For the selection of livestock farms, a threshold of 50 animal units at site is applied. For the calculation of different scenarios, it is possible to modify the diameter of the catchment area and the amount of fields selected within these areas.

Within the catchment area, the spatial process chain inventory analysis is carried out. The inventory modules for supply of biomass, transport and energy conversion are executed. The objective is to calculate the balance of amounts of biomethane to be produced, economic costs per unit of biomethane and the identification of greenhouse gas emissions per unit of biomethane, measured in kilowatt hour.

The balance for the raw and auxiliary materials of the different production steps for biomass cultivation on a specific agricultural field is carried out. The steps comprise the

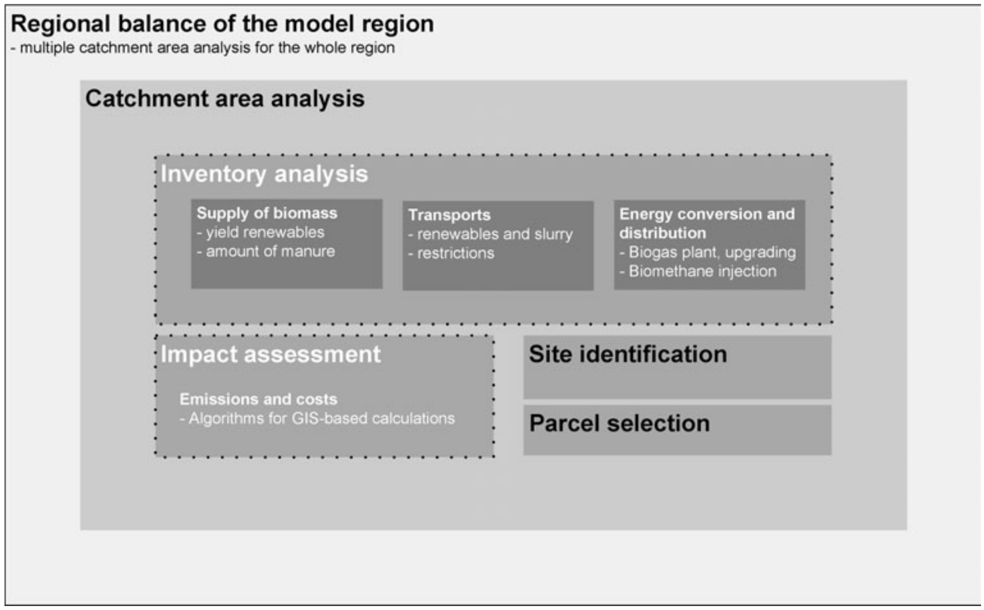


Fig. 2 Structure of the spatial model

application of fertilisers, seeds, plant protection agents as well as the fuel demand (diesel) of farm machines. The inventory for the calculation of costs and emissions of the supply with renewable resources is derived from agricultural databases (KTBL 2005, 2006). These datasets were used for all steps in the process chain up to the biogas plant. All emissions connected to the biomass supply are calculated in relation to the size and geometry of the agricultural fields and the amount of crop yielded. Based on these data, it was possible to derive an algorithm for different biogas substrates. The algorithms were implemented in the geoinformation system. Figure 4 shows an exemplary calculation base for the GHG emissions of the cultivation of maize. With rising size of cropping area and crop yield, the hectare-specific consumption of diesel fuel decreases. Through the application of GIS techniques and geospatial data describing the real agricultural area, raw and auxiliary materials as well as fuel consumption may be computed fast and easily. Other dependencies of raw materials and supplies which are based primarily on the relation to agricultural yield display the same relationship as with the diesel input in the example described.

The interface to the next process chain element is the field border, where the crop is loaded onto the transport vehicles. For the spatial inventory of the transport, the amount of biomass and the transport distance are balanced. The amount of biomass is a result of the preceding module; depending on this amount and the loading capacities of the transport vehicles the number of transport procedures can be calculated. With help of a GIS-based logistic tool, the shortest

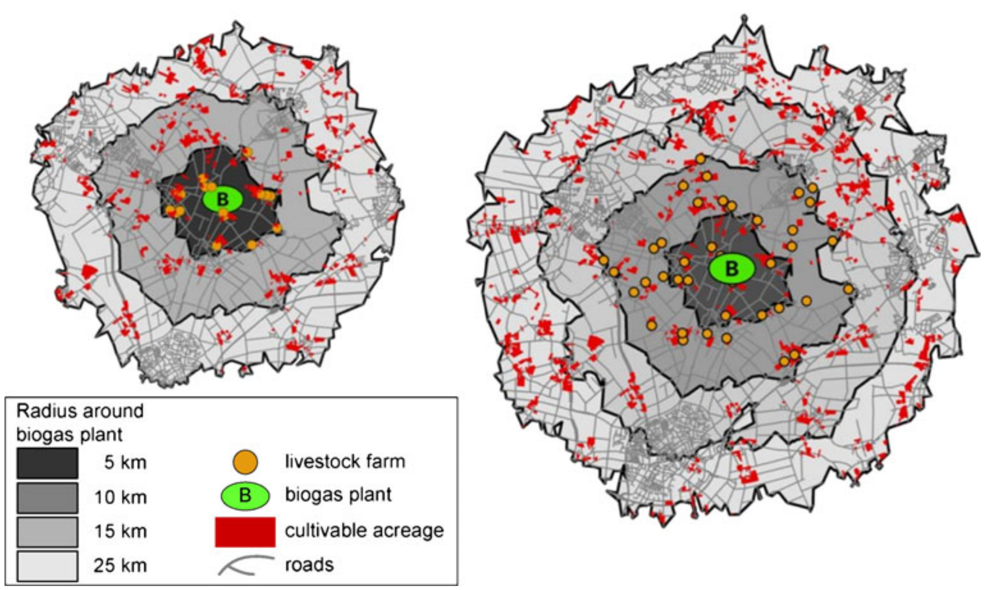


Fig. 3 Examples of computed catchment areas

Fig. 4 Algorithms for computation base of diesel demand for different field sizes and yields

yield c	factor a	factor b	factor d	factor e
...				
35	71,9250	-0,0483	50,4050	0,0666
36	75,3872	-0,0454	53,5739	0,0659
37	77,9616	-0,0433	55,9302	0,0654
38	80,3050	-0,0413	58,0750	0,0649
39	82,4286	-0,0396	60,0187	0,0645
40	84,3438	-0,0380	61,7716	0,0641
41	86,0618	-0,0366	63,3440	0,0638
42	87,5938	-0,0353	64,7463	0,0635
43	88,9512	-0,0342	65,9887	0,0632
44	90,1452	-0,0332	67,0815	0,0630
45	91,1871	-0,0323	68,0351	0,0627
46	92,0881	-0,0316	68,8598	0,0626
47	92,8595	-0,0309	69,5658	0,0624
...				

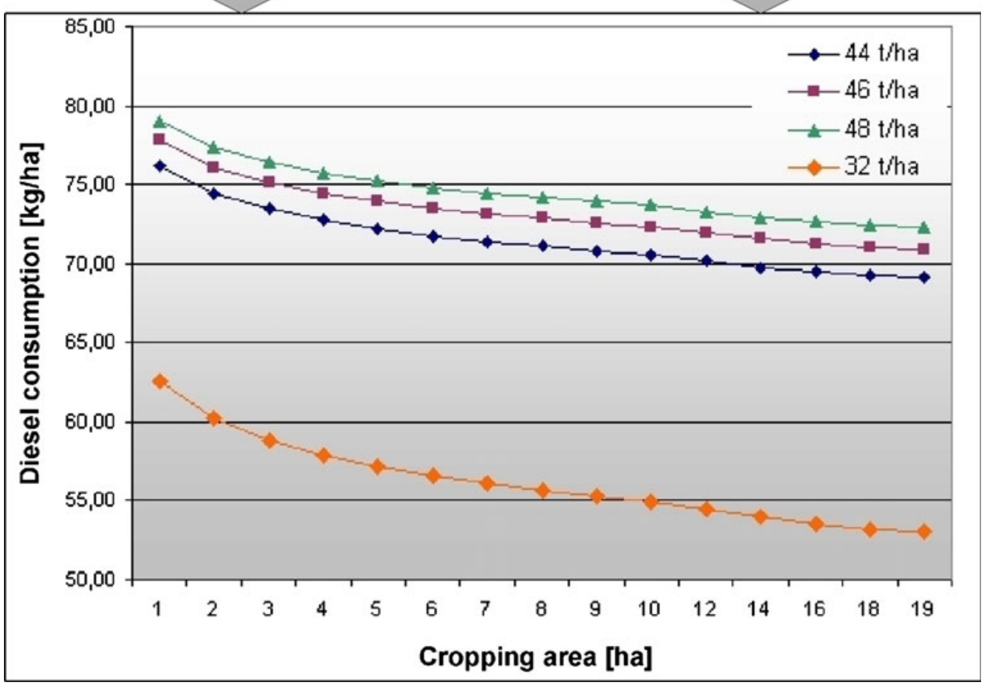
Algorithm for cropping area less than 20 ha

$$y = \frac{a * X^b}{c}$$

Algorithm for cropping area greater than 20 ha

$$y = \frac{d * X^e}{c}$$

c = yield of maize per ha [t/ha]
X = size of cropping area [ha]
Y = demand of diesel [kg/ha]



distances between the fields and the biogas plant are derived. Transport restrictions (avoidance of settlement passages, no transport on motorways) are integrated into the shortest distance calculations. For the balance of diesel used within this process chain element, the number of transport processes and the shortest distances between fields and plant sites are summed up. The same procedure is carried out for the transport of manure, starting at the stock farming and ending at the biogas plant.

The transition to the next process, chain element is just before the storage of the biomass. In the element "biogas plant algorithm for balancing the expenditures for storing biomass", the operation of biogas plant itself as well as the gas purification and injection are modelled.

The inventory for the balancing of substrate storage, loading and conditioning, fermentation processes, biogas conditioning and processing of fermentation residues is performed at the site of the biogas plant. Depending on the substrate mix being amassed in the catchment area (ratio between herbal substrates and manure), the configuration and operational mode of the biogas plant is arranged. These parameters are important for the calculation of raw and auxiliary materials like demand of diesel for ensilage of herbal material or the demand of power for feeding or

stirring devices. The substrate mixture is also important for the amount of biogas produced and hence necessary for the determination of electric power demand for upgrading biogas to biomethane, corresponding algorithms for calculation are integrated into the GIS application.

A crucial factor influencing the output of the inventory analysis is the amount of substrate being accumulated at the plant site. This can be influenced by the range of the catchment areas or the availability of fields for biomass. Different scenarios can be calculated for these factors using the GIS-based methods. In the following, the results for the so-called basic scenario are presented. The determination of the share of biogas substrates in the energy crop production is built on the reference scenario (BMU 2007; Fritsche et al. 2004) which has proved to provide a quite realistic estimate of the areas actually used for biogas generation in 2007. In order to define this share of the total energy crop production, forecasts on the development of biofuel production (bioethanol, biodiesel) were also included. The area available for biogas substrates according to the reference scenario for Germany is set in the following way: 2010, 0.48 million ha; 2020, 0.74 million ha; 2030, 1.44 million ha; 2040, 2.37 million ha; 2050, 3.43 million ha. The aforementioned available area amounts for biogas substrates have to be regarded as overall values for Germany, without giving details on a regional distribution. Therefore the regional distribution has to be adjusted to the model region with the help of an economic agricultural model, which is needed for a higher resolution of the description regarding the current situation in the model regions.

3 Results

The integration of an economic agricultural model into the reference scenario (a national potential calculation) is considered as a regional potential calculation and the basis for the (regional) balances. Based on the availability of fields for biogas substrate production provided by the reference scenario and RAUMIS, the results show a possible distribution of biogas plants in the model regions as described in Fig. 5. For the model region "Lower Rhine", ten biogas

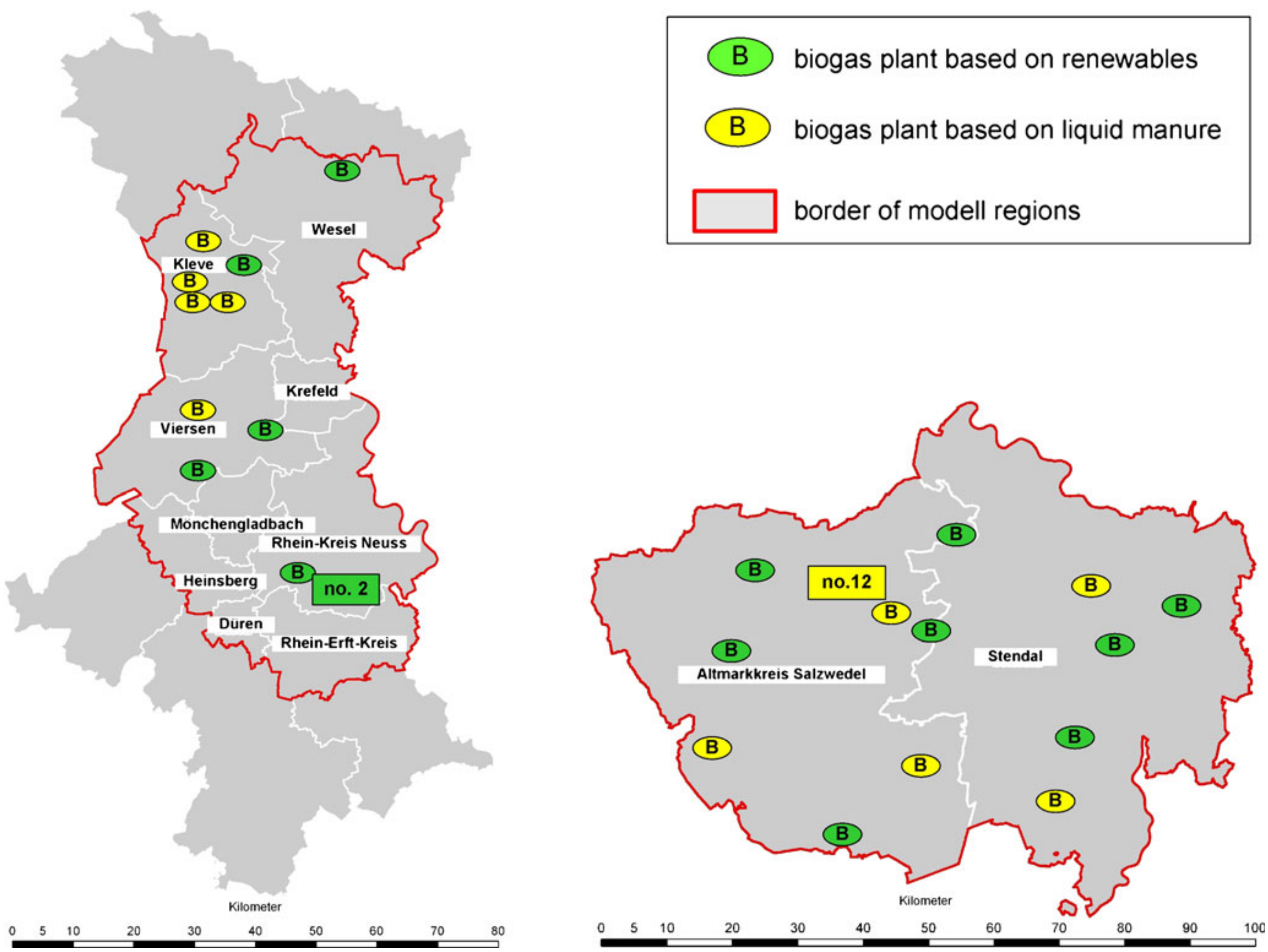


Fig. 5 Biogas plant sites in the two model regions

Table 1 Specific values of two individual sites, reference scenario

Biogas plant no.	Substrate mixture (fresh mass)		Upgraded biogas produced (Nm³/h)	Production costs (ct/kWh $H_{i,N}$)	GHG emissions (g CO_{2e}/kWh $H_{i,N}$)
	Maize (*t*)	Manure (*t*)			
2 (Lower Rhine Region)	61,560	37,629	876	7.50	99.8
12 (Altmark Region)	0	60,091	100	9.42	−7.2

plants can be installed whereas 13 plants are possible in the Altmark region.

3.1 Balances of individual sites

Detailed descriptions of results regarding the potential analyses or plant balances are conducted for site no. 2 (renewable-based biogas plant) in the Lower Rhine region and no.12 (plant based on liquid manure) in the Altmark region (see Fig. 5). Basic characteristics of these plants with regard to substrate input, biomethane amounts, production costs and GHG emissions are displayed in the following Table 1.

The composition of the substrates varies according to site and catchment area and lead to large variations in plant configurations and cost structures (see Table 1). In the catchment area of plant 2 in the Lower Rhine region, approximately 61,560 t silage maize (fresh weight) and additionally about 37,629 t liquid manures (fresh weight) have been identified. On site 12 in the Altmark region, however, maize as substrate is not available. The potentials are bound by eight other biogas plants in the region. Plant no. 12 is fed entirely with liquid manure as substrate input. The results of plant-specific emission balances vary between all plants, as explicitly shown in Table 2.

The results of GHG balances show that the maximum emissions are released during the step energy crop production (consisting of cultivation, maintenance and harvesting) which is attributed mainly to production and application of fertilisers and plant protection agents as well as the fuel demand of farm machines. These calculations include the good practice application of digested biomass discharge as a substitution of mineral fertilisers, resulting in countable GHG allowances. However, it has to be taken into account that the lack of available knowledge on GHG emissions due to the application of fertilisers causes uncertainties in the balancing (i.e., release of nitrous gas, which is hardly investigated, subject to many variations in the micro scale range). It is noteworthy that the substrate transports to the biogas injection plant and substrate storage have no major impact on the emission balance of biogas plants.

Studies reveal that basically a prioritised or exclusive application of liquid manures as basic substrate leads to a very low release of GHG emissions in the overall balance, since very high GHG allowances are issued for the fermentation of liquid manure (Holm-Nielson et al. 2009; Mueller 2006). As shown by example plant no. 12, biogas installations based on liquid manure may possibly even act as greenhouse gas sinks. Without input of energy crops, and in combination with the allowances for low GHG emissions due to substitution of fossil fertilisers by the application of liquid manures, the balancing yields a negative sum, i.e. per definition a greenhouse gas sink.

Table 2 Greenhouse gas emissions for the whole process chain of two biogas plants

Step in process chain	Biogas plant no. 2 (Lower Rhine region)	Biogas plant no. 12 (Altmark region)
	GHG emissions [g CO_{2e}/kWh $H_{i,N}$]	
Energy crop production	43.2	Not applicable
Transport of renewables	>0.1	Not applicable
Transport of manure	>0.1	<0.1
Storing	0.4	Not applicable
Loading	1.1	Not applicable
Conditioning (substrates)	5.0	0.7
Biogas plant	26.9	27.8
Digestate storage	0.5	35.5
Conditioning (biogas)	31.5	35.5
Allowances for liquid manures and replacement of mineral fertilisers	−9.2	−77.6
Sum	99.8	−7.2

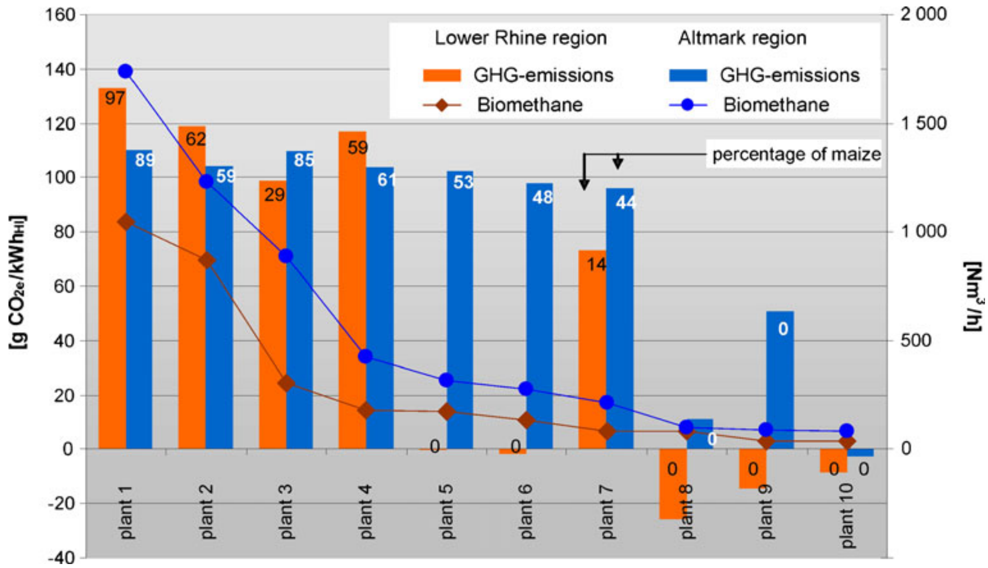


Fig. 6 Specific GHG emissions for each biogas plant site in the two model regions

3.2 Region balances

The results from the analysis of the single sites in the model regions are compiled as illustrated in Fig. 6. This method allows an upscaling and hence a regional balance including the identification of a regional biogas potential, the costs involved (investment costs, regional added value) and the GHG reduction potential for both model regions.

The average specific GHG emissions per kilowatt hour gas generated (reference heating value $H_{i,N}$) amount to 77 g CO_2 equivalents per kilowatt hour ($H_{i,N}$) in the Lower Rhine Region and to 83 CO_2 equivalents per kilowatt hour in the Altmark region.

3.3 Dynamic development of land availability and the biomethane potential

The land available for the cultivation of renewable resources, in this case particularly biogas substrates, is the most important parameter for the determination of biogas potentials and hence for the total amount of emissions from biomass utilisation (Table 3). As the agricultural land availability increases continuously over the evaluation period, the sustainable amount of regional biomethane potential is also rising. The amounts of liquid manure are assumed to remain steady due to a constant number of livestock and thus have no positive impact on the development of the biomethane production. The results reveal that the share provided by liquid manure in the total biogas potential is decreasing and as a consequence will be increasingly marginal for climate change adaptation measures in forthcoming decades.

Along the gradually rising availability of agricultural area, the biogas injection plant sites may be further expanded, while the specific costs of gas generation can be reduced. Nevertheless, the specific GHG emissions slightly rise, despite potential GHG allowances, since the additional GHG emissions from biomass production and transport cannot completely be outweighed by efficiency improvement measures in the plant operation.

4 Discussion

The results of the balances of the individual sites in the model region are compiled for the balancing of the entire

Table 3 Prediction of land availability, specific manufacturing costs and specific GHG emissions in the model region Lower Rhine region, regional balance for reference scenario

Year	Cultivable area (ha)	Cultivable area (%)	manufacturing cost (ct/kWh $H_{i,N}$)	GHG emissions ($g\ CO_{2eq}/kWh\ H_{i,N}$)	
				Without bonus	With bonus
2010	3,960	3.1	8.18	101.3	77.0
2020	6,100	4.8	7.79	103.6	83.8
2030	11,120	9.2	7.22	105.8	90.4
2040	16,970	15.2	6.69	106.9	93.6
2050	22,830	22.0	6.21	107.4	95.1

region. This allows the determination of the biogas potential, of the costs (investment cost, regional added value) and the GHG reduction potential for both regions, the Lower Rhine and Altmark areas.

Noteworthy are the differences between the regions concerning the agricultural structure. In the Altmark region, a considerably larger area is available than it is the case in the Lower Rhine region. This is due to the larger scale of farms and cropping area in the Altmark. Furthermore, the regionally specific differences in livestock farming lead to different gas production costs. For example in the Lower Rhine region, farming dominated by pig farms causes much higher amounts of manure that contains low energy and has lower methane production rates which requires specifically larger container dimensions and therefore involves higher costs.

The average specific GHG emissions per kilowatt hour gas produced ($H_{i,N}$) amount to 77 g CO_{2e}/kWh ($H_{i,N}$) in the Lower Rhine region and to 83 g CO_{2e}/kWh ($H_{i,N}$) in the Altmark region. In the model region Lower Rhine, the high amount of farming manure due to intensive livestock farming has led to considerable GHG allowances and thus to lower specific GHG emissions. These results were calculated with an average production capacity per area. There are differences when 2 years or several administrative districts with varying yields per area are directly compared to each other. This underlines the need to include variations in the inventory to take these aspects into consideration.

Taking a closer look into the GHG emissions in the related process chain elements, it also becomes evident that the efficiency of the plant and therefore its size play an important role: the bigger the size of a renewable energy plant, the more (energy) efficient is the production of biogas. The specific demand of electricity for the fermenter, mixing and process technological systems, which have high GHG emissions (German electricity mix, 0.61 CO_{2eq}/kWh) decreases considerably with the size of the plant and leads to an oversized compensation of the slowly rising transport emissions.

As a conclusion, it can be stated that big size biogas injection plants with gas production capacities of 1,000 Nm^3 of biomethane and more are operating not only more energy efficient, but also more environmentally friendly.

From the ecological point of view, regarding GHG emissions, large biogas installations based on high amounts of farming manure may seem quite efficient at a first glance. Emissions caused due to transport are more than outweighed by considerable allowances for liquid manure digestion (prevention of GHG emissions). The GHG bonuses are a counterbalance in particular for the expenses for energy crop cultivation and the resulting emissions. Emissions occurring during the transport of liquid manure are rather low and hardly affect the GHG balance. Leaving GHG emissions and production costs behind, biogas plants fed with liquid manure from within a radius of more than 10 km, however, do not comply with sustainability criteria, since the transportation involves enormous logistics and is bound to encounter acceptance problems in the public. For the logistics of the plant type with a supply radius for renewable resources of 25 km and for liquid manures a radius of 5 km an annual amount of about 9,000 lorry tours is required (one-way), as well as the same amount of tours for the transportation of digestion residues. Another problem is the logistics at the plant site itself because more than 25 lorries have to be unloaded daily.

5 Conclusions

The application of GIS technologies permits a plant-specific assessment of the greenhouse gas emissions, of the real available biogas potentials and the costs of their exploitation. In contrast to previous studies, now the contribution to GHG reduction and the resulting avoidance costs of a specific plant, including all involved cropping areas, may be identified on a regional basis. Additionally, GIS tools do not only allow the assessment of individual plants, but also the determination of the GHG reduction potential, the biogas potential as well as the necessary investment costs for entire regions.

As was shown, not only changes in microspatial environmental parameters have an effect on the resulting balances. Even process chain elements independent of location get a spatial reference with the application of a catchment area analysis. This is a consequence of the specific substrate mixture which is generated by the regional distribution of substrates and the mixing ratio at the biogas plant. To improve the accuracy of the balances calculated by the GIS tool, further implementations of environmental parameters like soil-related nitrous oxide emissions can be implemented.

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